Use of Drill-Bit Energy as a Downhole Seismic Source

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SUMMARY

A new borehole seismic technique, the Tomex Survey™, uses the seismic emanations produced by a drill bit during drilling as a downhole energy source. No downhole instrumentation is required for collection of the seismic data, and the data recording does not interfere with the drilling process. The drill-bit-generated signals are recorded with sensors attached to the top of the drillstring and at various surface-geophone locations near the well. The sensor output at the top of the drillstring is used as a pilot signal for cross-correlation with the signals recorded at the surface-geophone positions. Cross-correlation is used to determine arrival times and to enhance the signal-to-noise ratio of drill-bit-generated events. Deconvolution and time shifts are performed to remove the effects of recording the pilot signal at a location which is distant from the location of the source of energy at the drill bit. A direct comparison between data collected using a drill-bit source and conventional VSP data shows that the drill-bit source yielded comparable data quality.

In using the drill bit as a downhole seismic source for inverse VSP, many of the limitations in conventional VSP are overcome. Several applications for VSP that were previously considered by some explorationists to be prohibitively expensive are now feasible. Furthermore, this measure-while-drill technique offers the potential for the explorationist to make real-time drilling decisions on site.

INTRODUCTION

Since its introduction, Vertical Seismic Profiling (VSP) has gained limited acceptance within the geophysical community. This is largely due to the long acquisition time and associated high costs, both in terms of rig time and equipment time, required to obtain comprehensive large-offset data over an extended depth interval. Costs are typically lowered by reducing the number of levels recorded, but this reduction results in lower-fold data and reduced resolution. Single-offset surveys are the most common type of VSP survey, because multiple-source offset surveys capable of imaging formations away from the borehole are very costly.

The technique described here utilizes the natural vibrations created by the impacting teeth of a drill bit as a downhole seismic source, thus offering cost-effective borehole seismic surveys. Since the seismic data are acquired while the well is being drilled, costs associated with lost rig time are eliminated. This is especially important in offshore drilling where daily rates are very high. With the drill-bit source, data are acquired at finely spaced intervals in depth (as small as 1 ft in some cases) at reasonable cost and without the complications of open-hole wireline operations. Finally, since the drill bit is a downhole energy source rather than a surface source, multiple 2-D and even 3-D surface geophone deployments can easily be used.

These and other differences between the conventional VSP and the drill-bit-source VSP are summarized in Figure 1. Ultimately, the measure-while-drill nature of the drill-bit source will have an impact on real-time drilling decisions.

DATA ACQUISITION AND PROCESSING

Data acquisition is accomplished without the use of downhole instrumentation. The drill-bit-generated signal is monitored by means of a reference sensor attached to the top of the drillstring. The signal recorded at the top of the drillstring is used as a pilot signal, as in Vibroseis, for cross-correlation with signals from the surface geophones (Figure 2). The 'sweep' length is determined by the drilling rate and equals the time required for the drill bit to move a predetermined distance.

The cross-correlation process accomplishes two objectives. First, it establishes the relative travel-time differences between coherent energy in the pilot signal and the surface-geophone signals. This is achieved by compressing the continuous drill-bit-generated vibrations into distinct events with a time duration proportional to the signal bandwidth. Second, it enhances the coherent low-level signals sensed at both the top of the drillstring and at the surface geophones. Incoherent energy sensed by just one of the sensors behaves as additive noise to the cross-correlation. The improvement in signal-to-noise ratio is proportional to the product of the bandwidth and the sweep length of the data (Aki and Richards, 1984). Hence, with sufficient sweep times, even a coherent signal that is much lower than the incoherent noise level can be detected after cross-correlation.

From our experience, the dominant energy represented in the cross-correlation is from the vibrations generated by the rotating teeth of the drill bit impacting the formation. This is not a surprising result considering that the drill bit acts with large dynamic forces (Deily, et al., 1968). This 'bouncing' of the bit generates a sequence of impulses that are imparted into the formation and into the drillstring. However, the drill-bit-generated signals sensed at the surface-geophone locations and at the top of the drillstring are modified by travel through the earth and the drillstring, respectively. Hence, the cross-correlation spectrum exhibits a spectral shaping due to both of these travel paths that can be expressed in Z transforms as follows:

$$\mathrm{XCOR}\,(Z) = \mathrm{PILOT}\,(1/Z)\ \mathrm{GEO}\,(Z)$$

where:

PILOT (1/Z) = Z transform of the time-reversed pilot signal

GEO (Z) = Z transform of the field geophone signal

and

$$\mathrm{PILOT}\,(Z) = \mathrm{BIT}\,(Z)\ \mathrm{DS}\,(Z)$$

$$\mathrm{GEO}\,(Z) = \mathrm{BIT}\,(Z)\ \mathrm{EARTH}\,(Z)$$

where

BIT (Z) = Z transform of the drill-bit-generated signal

DS (Z) = Z transform of the drillstring impulse response

EARTH (Z) = Z transform of the desired earth impulse response.

With conventional Vibroseis recording, the pilot signal approximates the source signal, and hence there is no travel-path distortion present in the pilot signal.

The transfer function of the drillstring has been analyzed previously (Dareing, 1982). Resonant frequencies due to multiples within the bottom-hole assembly, f_{BHA}, and the drillpipe, $f_{drillpipe}$, are determined by the following relations:

$$f_{BHA} = \frac{n\,V_{steel}}{4\,L_{BHA}} \quad (n = 1, 3, 5, ...)$$

$$f_{drillpipe} = \frac{n\,V_{steel}}{2\,L_{drillpipe}} \quad (n = 1, 2, 3, ...)$$

where:

L_{BHA} = length of bottom-hole assembly

$L_{drillpipe}$ = length of the drillpipe

V_{steel} = velocity of sound in steel ($\sim$4875 m/s).

Since the drillpipe is much longer than the bottom-hole assembly, the frequency separation between resonance peaks introduced by the drillpipe travel path is much smaller than the separation between the resonance peaks created by the presence of the drill collars. The predicted frequency separation between resonance peaks for a drillpipe that is 900 m long is ~2.5 Hz, which coincides with the peak spacings observed in Figure 3 for a spectrum recorded at the top of such a drillstring. The drillstring resonance peaks appear in the time domain as short-path multiples related to the length of the bottom-hole assembly and long-period multiples related to the length of the drillpipe. As the well is being drilled, the bottom-hole assembly is seldom changed, while the drillpipe length is proportional to the well depth. Hence, the long-period multiples of the drillstring show an increase in time delay with depth. This is illustrated in Figure 4, which shows one side of several pilot-signal autocorrelation functions recorded at a typical well. The first-, second-, and third-order drillpipe multiples are distinct events.

To remove the multiples and the spectral shaping of the pilot signal present in the cross-correlated signal, a signature-deconvolution operator must be applied to the cross-correlated energy response. This operator is derived from the pilot signal.

The Z transform of the pilot signal autocorrelation is:

$$\begin{aligned} AUTO_{pilot}(Z) &= PILOT(1/Z)\ PILOT(Z) \\ &= DS(1/Z)\ BIT(1/Z)\ BIT(Z)\ DS(Z) \end{aligned}$$

With the assumptions that the drill-bit-generated energy is white and the drillstring impulse response is minimum phase, an operator that is a one-sided inverse of the pilot signal autocorrelation, will remove the multiples and associated resonances of travel within the drillstring from the cross-correlated output.

In terms of Z transforms,

$$OP(Z) = 1/DS(1/Z)$$

and

$$\begin{aligned} [OP(Z)]\ XCOR(Z) &= [1/DS(1/Z)]\ DS(1/Z)\ BIT(1/Z)\ GEO(Z) \\ &= BIT(1/Z)\ GEO(Z) \\ &= [BIT(1/Z)\ BIT(Z)]\ EARTH(Z). \end{aligned}$$

The product, BIT (1/Z) BIT (Z), the autocorrelation of the drill-bit-generated signal, is the counterpart of the Klauder wavelet in correlated Vibroseis data.

The propagation of the drill-bit-generated signal through the drillstring not only generates multiples and alters the spectrum of the drill-bit signal, it also induces a time shift in the cross-correlated output so that the cross-correlated arrival times are advanced by the time it takes for energy to travel from the drill bit to the top of the drillstring. This time shift is equal to the length of the entire drillstring (including the bottom-hole assembly) divided by the velocity of sound in steel. By adding this delay to the cross-correlated data and removing the effects of the pilot signal present in the cross-correlations, the cross-correlated data are transformed into the equivalent of a conventional vertical seismic profile.

COMPARISON WITH VSP DATA

In accordance with the reciprocity principle, the arrivals observed in a VSP section should be the same as those observed in an 'inverse VSP' using a downhole source such as the drill bit. This equivalence assumes that the source and receiver antenna patterns and impulse responses are interchangeable. For near-offset source/receiver locations in a horizontal medium, the direct and reflected wavefields arrive at nearly vertical incidence, which suggests that the effects of the antenna pattern in a comparison of a conventional VSP and an inverse VSP should be negligible. A wavelet-matching operation can be used to ameliorate any differences due to source and receiver responses.

Data acquired at the same surface location were used to compare the direct-arrival energy from a conventional VSP survey and the drill-bit-source inverse VSP survey. The VSP was acquired with an airgun source. The downhole receiver was positioned over a depth interval where drill-bit-generated energy had been previously recorded during the initial drilling of the well. The source/receiver offset from the wellhead was 750 m. Figure 5 shows the full wavefield display for each technique. The drill-bit-source data contain traces spaced at 3 m depth intervals whereas the conventional VSP spacing was 20 m, hence for purposes of comparison, the drill-bit-source data were decimated. The general signal-to-noise character of the data is similar.

CONCLUSIONS

The Tomex Survey technique involves the acquisition and processing of drill-bit-generated signals produced during the drilling of a well to yield data in a form similar to that of a conventional VSP. This result is achieved without interrupting the drilling operation, and without the use of any downhole instrumentation. A one-to-one comparison with a conventional offset VSP yielded comparable signal-to-noise ratios. The use of the drill bit as a seismic source is expected to open up many new applications for vertical seismic profiling.

ACKNOWLEDGMENT

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TOMEX SURVEY	VSP
• Measure While Drill -- Fine depth spacings (<3 m) -- Predict ahead of bit capabilities -- No lost rig time -- Necessary to incorporate survey into drilling plan	• Acquired After End of Drilling -- Coarse spacings (>10 m) -- No predict ahead ability unless drilling is interrupted -- Lost rig time (8-48 hours) -- Can acquire data after a well has been drilled or temporarily suspended
• Downhole Drill-Bit Source -- No downhole instrumentation -- No borehole risk -- No clamping or casing effects -- Signal influenced by drilling conditions -- No temperature or pressure limitations	• Downhole Wireline Receiver -- Expensive tool -- Borehole and tool risk -- Tool locking, casing, and hole conditions affect signal -- Signal unaffected by drilling conditions -- Cannot run in holes with high temperatures -- Data acquired deep in a borehole in a relatively noise-free environment
• Surface Geophone Receivers -- Can acquire many surface locations inexpensively -- Fewer problems with access/permitting -- Additive surface noise can degrade data -- Can bury geophones beneath weathered layer (increased SNR and bandwidth)	• Surface Source -- Expensive to acquire multiple surface locations -- Difficult or impossible to access and permit many locations -- Coupling problems with the near surface

FIG. 1. Comparative characteristics of drill-bit-source technique vs. conventional VSP.

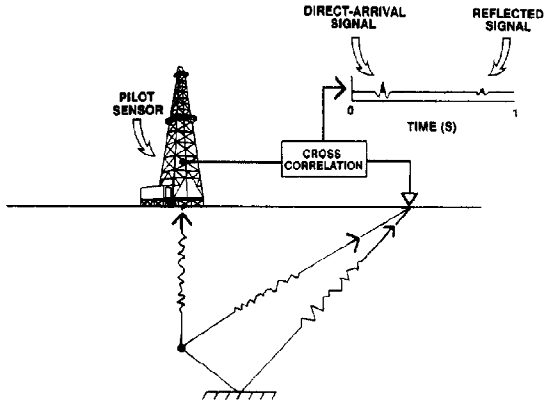

FIG. 2. Diagram showing how seismic energy propagates from drill bit to pilot sensor and to geophones.

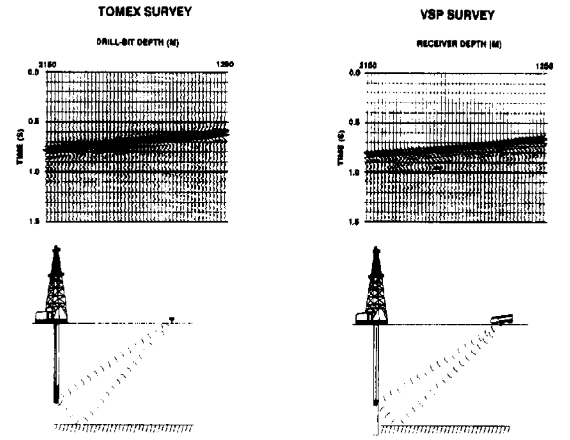

FIG. 5. Comparison between drill-bit source inverse VSP and conventional VSP full wave field data.

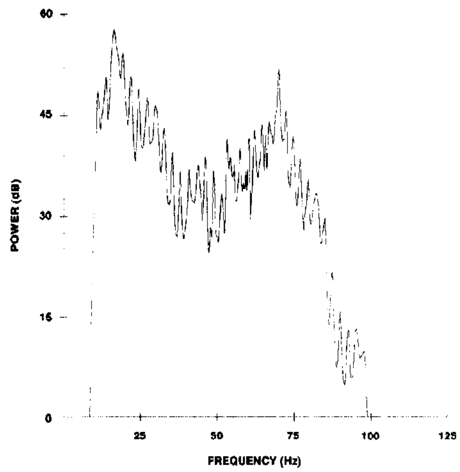

FIG. 3. Pilot-signal spectrum from a drilling depth of 900 m. Resonance peaks spaced at 2.5 Hz are due to drillpipe multiples.

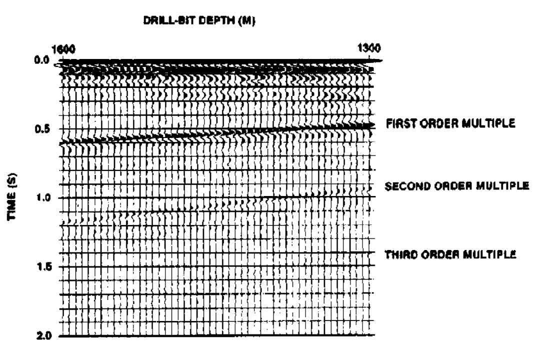

FIG. 4. Pilot-signal autocorrelations for drilling depths from 1300 to 1600 m. Depth spacing is 6 m.